ELECTRICAL AND ELECTRONIC MATERIALS

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Lecture: 3 Tutorial: 1 Total: 4

Dr. Ahmed Mohamed Azmy

Department of Electrical Power and Machine Engineering

Tanta University - Egypt

Faculty of Engineering

Tanta University

Magnetic Materials

The description of the interaction of materials with magnetic fields is equivalent to that with the electric field

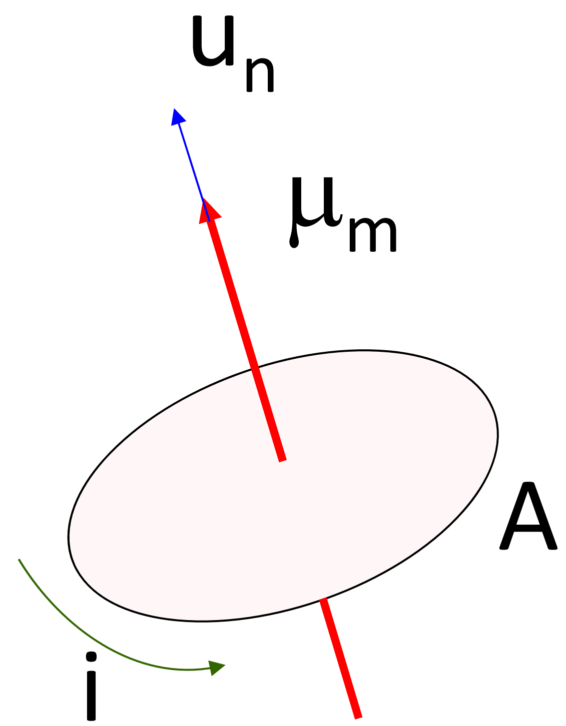
The magnetic field is characterized by the magnetic field intensity with units of Ampere-turn/meter (A/m), and the magnetic flux density with units of Weber/m^2 (Wb/m^2) or Tesla

Obviously, B and H are vectors

Magnetic Dipole Moment

The torque acting on a current-carrying coil can be related to the characteristics of the coil by the magnetic moment or magnetic dipole moment

For the current loop, the circulating current is **I** and the area enclosed by the current is **A**



Magnetic Dipole Moment

The magnetic dipole moment μ_m is defined as:

$$\mu_m = i\ A\ u_n$$

Where, $\mathbf{u_n}$ is a unit vector perpendicular to the area **A**

The magnetic moment is a vector with direction perpendicular to the current loop in the right-hand-rule direction

With **N** loops, the equation is multiplied by (**N**) as:

$$\mu_m = N\, i\ A\ u_n$$

Magnetic Dipole Moment

When the magnetic dipole moment is inserted inside a magnetic field, it will be subjected to a magnetic force (including both sides of the coil) and it will rotate to have its axis in the direction of the magnetic field

The torque exerted by the magnetic force is given by:

$$T_m = \mu_m \, B \sin(\theta) = i \, A \, B \sin(\theta)$$

Fields, Fluxes and Permeability

A basic relation between the magnetic flux density **B** and the magnetic field strength **H** in vacuum is given by Maxwell equation:

$$B = \mu_o \; H$$

Where μ_o is the magnetic permeability of the vacuum

($\mu_o = 4\pi \cdot 10^{-7}$) Henry/meter (H/m)

The relation between ε_0 and μ_0 is given as:

$$\boxed{\varepsilon_0 \cdot \mu_0 = \frac{1}{c^2}}$$

Where, **c** is the speed of light in free-space

Fields, Fluxes and Permeability

From Ampere's law:

$$\oint_c H \cdot dl = i_{inclosed} \Rightarrow H \cdot L = N \cdot i$$

Therefore, for a solenoid carrying a current of **i** and has **N** turns with **L** mean length, the flux density is:

$$\boxed{B = \mu_o \; H = \mu_o \, (N \; i/L)}$$

With the vacuum is replaced by any material, the relation between magnetic field strength and magnetic flux density is given as follows

$$B = \mu_o \; \mu_r \; H$$

Fields, Fluxes and Permeability

$$B = \mu_o \mu_r H$$

Where, μ_r is the relative permeability of the material

The relative permeability of the material μ_r is analogy to the dielectric constant ε_r

It is convenient to split **B** into the flux density in the vacuum plus that part in the material

The interaction of materials with a magnetic field is represented by the magnetization density $\vec{M}$ with similar units like $\vec{H}$ (i.e. A/m)

The magnetic vector $\vec{M}$ is defined as the magnetic dipole moment per unit volume

Fields, Fluxes and Permeability

The relation between $\vec{B}$, $\vec{M}$ and $\vec{H}$ is given by

$$\boxed{\vec{B} = \mu_0 (\vec{H} + \vec{M})}$$

We can also define the magnetic polarization **J** in analogy to the dielectric case as follows

$$\boxed{J = \mu_o \ M}$$

The relation between $\vec{B}$, $\vec{H}$ and J takes the form:

$$\boxed{B = \mu_o \mu_r H = \mu_o H + J = \mu_o H + \mu_o M}$$

$$\boxed{M = (\mu_r - 1) \ H}$$

Fields, Fluxes and Permeability

$$\boxed{M = (\mu_r - 1)\ H}$$

$$\boxed{M = \chi_{mag}\ H}$$

With $\chi_{mag} = (\mu_r - 1)$ is magnetic susceptibility that describes the response of a material to a magnetic field similar to dielectric susceptibility $\chi_{dielectr}$

In normal cases, the entire material will exhibit no net magnetic field

Similar to the case of electrical fields, if an external magnetic field is applied, the domains orient themselves along the applied field

Types of Magnetisms

The behaviour of magnetic materials under external magnetic has two forms

The first case is when the atoms of the material do not have natural net magnetic moment

This is the case with the elements having even atomic numbers and therefore an even number of electrons "diamagnetic materials"

The magnetic moments of spins cancel themselves

The second case is when some of the atoms of the material have a net magnetic moment with their own

That covers all atoms with odd numbers of electrons which therefore have one spin moment left behind "paramagnetic materials"

Types of Magnetisms

Sometimes, the magnetic materials are distinct in five groups: diamagnetic, paramagnetic, ferromagnetic, anti-ferromagnetic and ferrimagnetic materials

Many materials used as dielectrics are nonmagnetic, with $\mu_r = 1$

Diamagnetic materials have small negative value of χ_{mag} with $\mu_r \approx 1$ but is always less than 1

Paramagnetic materials have small positive values of χ_{mag} with $\mu_r \approx 1$ but is always greater than 1

A special form of paramagnetic materials is the ferromagnetism, e.g. iron, with a very-large positive value of χ_{mag} and $\mu_r >> 1$

Diamagnetic Materials

Changing the field strength induces currents

Current flow produces magnetic fields

Lenz's law defines the direction of the current and the field to be always in opposite direction to the generating forces

This results in an ant-parallel direction of the induced magnetic moment to the external field

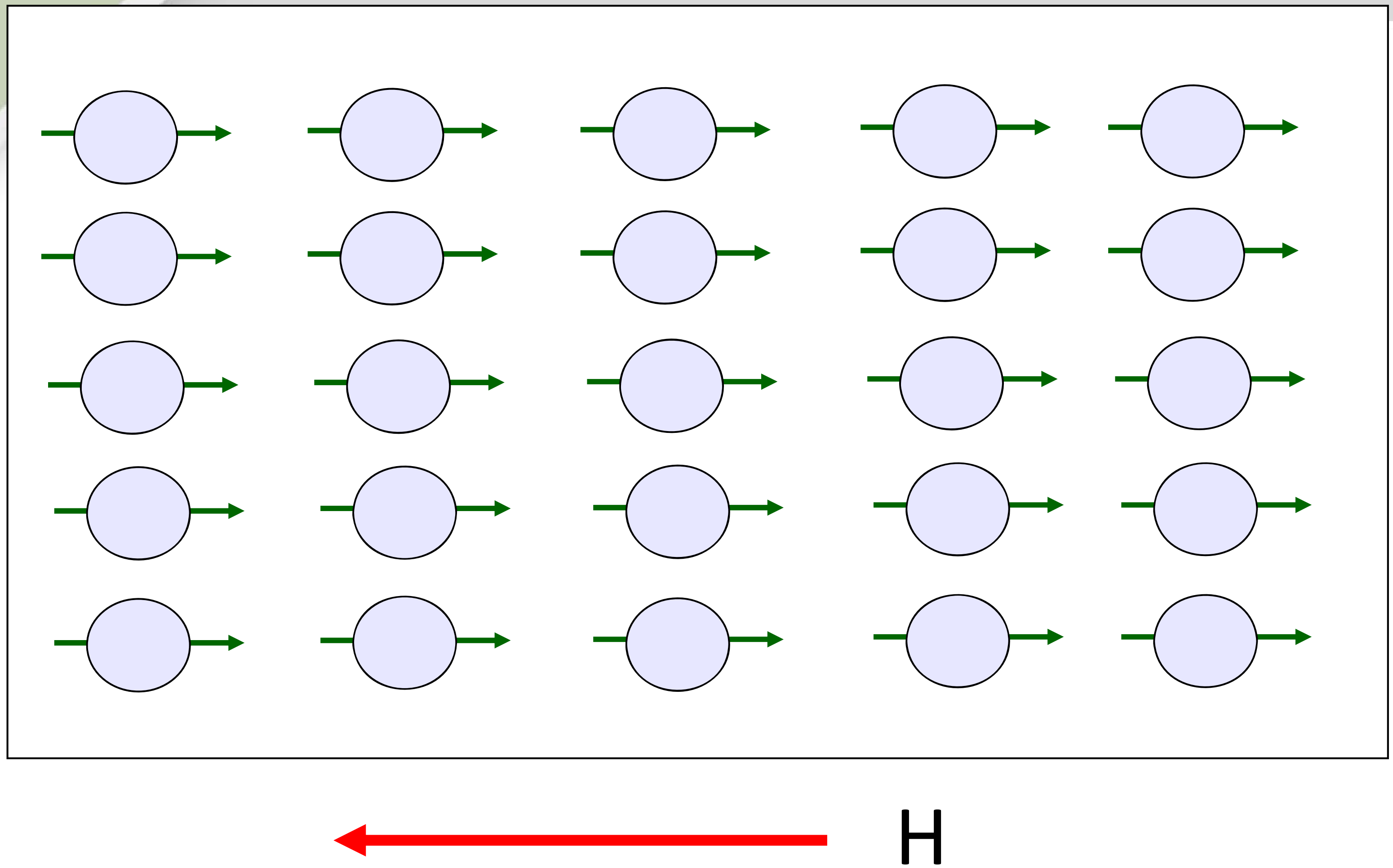
This is called diamagnetism and it is known to have a weak effect in normal materials

An exception is the superconductors which are materials with zero resistance at low temperature

Characteristics of diamagnetic materials

- They do not contain natural magnetic moments without external magnetic fields
- The value of μ_r is slightly less than 1, i.e. $\mu_r \leq\approx 1$
- In superconductors, which represent ideal diamagnetic materials, this value is zero, i.e. $\mu_r = 0$
- They respond to external fields in such a matter that currents and small magnetic moments are induced when turning on the field due to the light disturbance of the orbiting electrons
- The induced magnetic moments oppose the field

Characteristics of diamagnetic materials



Paramagnetic and ferromagnetic materials

Materials contain some atoms carrying a permanent magnetic moment can have internal interactions of the magnetic moments in addition to the interaction with external fields

weak internal interaction
paramagnetic materials

strong internal interaction
ferromagnetic materials

At high temperatures, the strong interaction of the second class will turn into the first class due to the high increase of the thermal energy.

Paramagnetic Materials

The behaviour of paramagnetic material is similar to that of the orientation polarization

The material contains permanent dipole moments with no or negligible interaction between them

The permanent dipole moments are free to be point in any direction even in solids

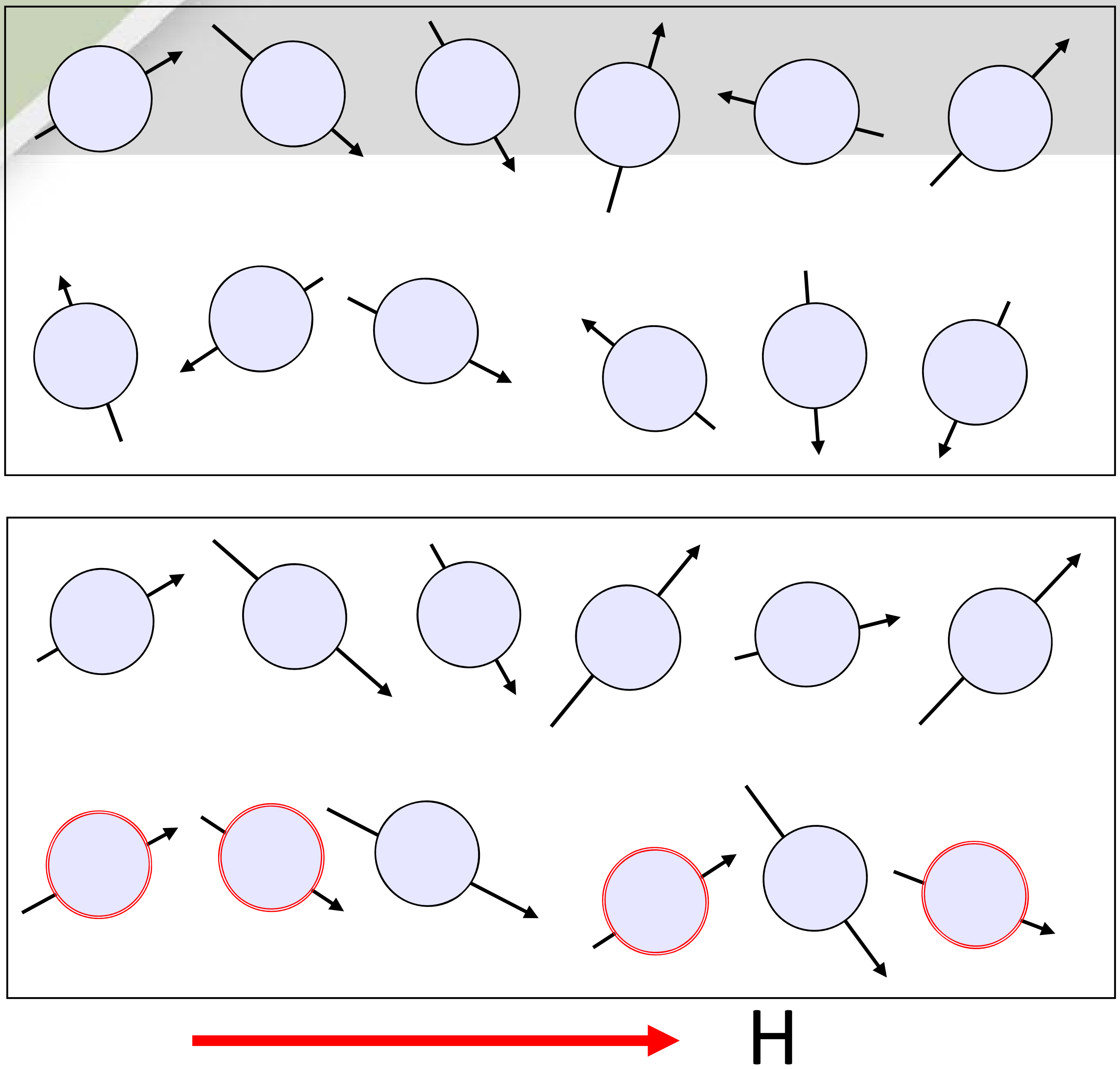
Under the effect of an external magnetic field, the magnetic dipole moments tend to adjust themselves in the direction of the field

This is opposed by the thermal energy or simply the entropy of the system

Characteristics of paramagnetic materials

- They have magnetic moments with weak magnetic interaction
- They have unordered regions (i.e. unordered magnetic structure) that fluctuate in time
- The average value of the permanent magnetization over time is zero
- They respond to external fields in such a matter that only small average orientation in field direction is present with mechanism similar to orientation polarization for dielectrics
- The value of μ_r is slightly greater than 1, i.e. $\mu_r \gtrapprox 1$

Characteristics of paramagnetic materials



Characteristics of ferromagnetic materials

- They have magnetic moments with strong magnetic interaction
- They have ordered regions that are stable in time
- The average permanent magnetization is obtained by the vector sum of individual magnetic moments
- There are some Kinds of ordering like **ferro-**, **antiferro-**, and **ferrimagnetisms**
- They respond to external fields by forming large component of magnetic moment in field direction

- For ferromagnetic materials $\mu_r >> 1$
- For anti-ferromagnets $\mu_r \approx 1$
- For ferrimagnetic materials $\mu_r > 1$

Characteristics of ferromagnetic materials

Ferromagnetism

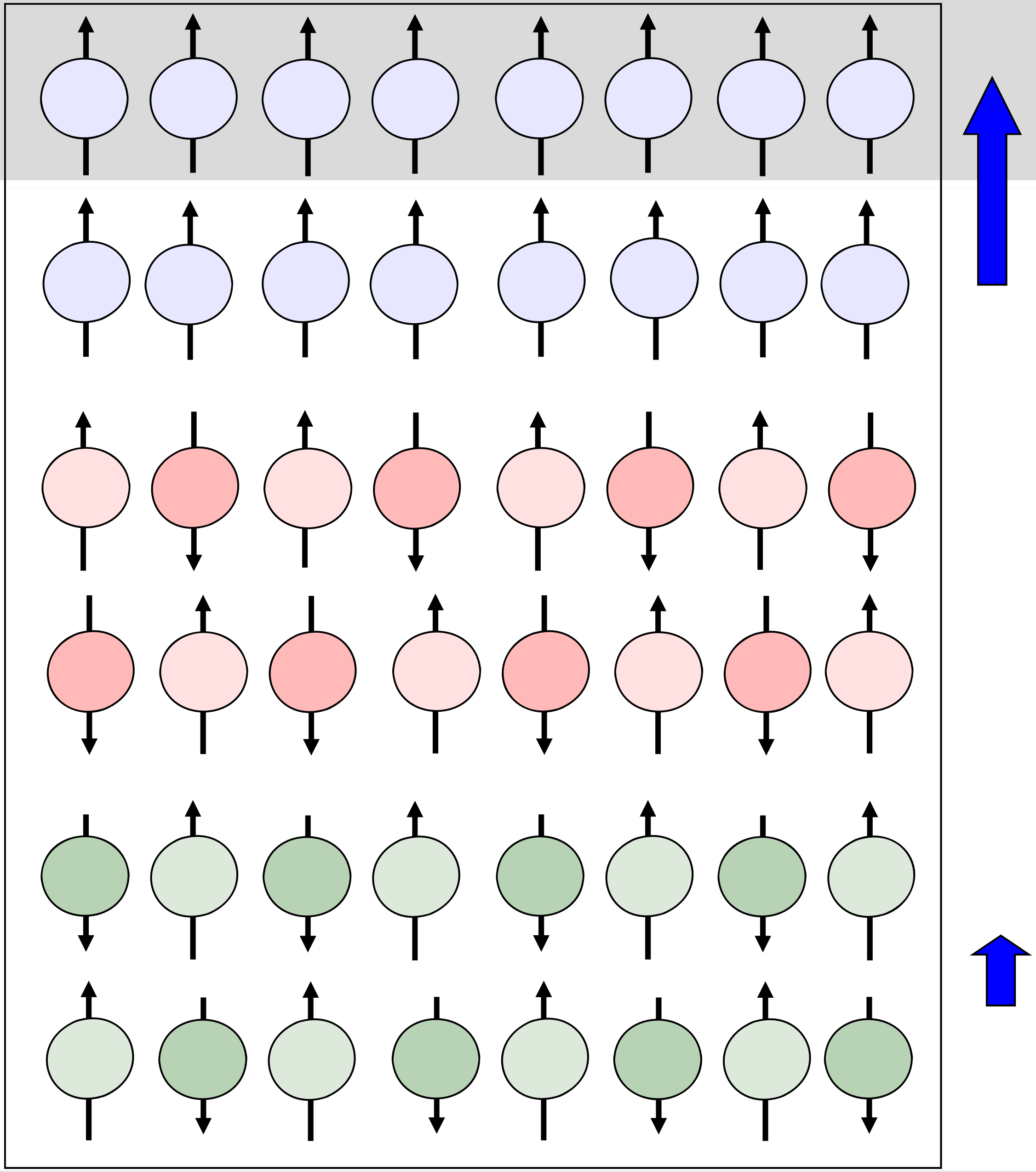
$\mu_r >> 1$

Anti-ferromagnetism

$\mu_r \approx 1$

Ferrimagnetism

$\mu_r > 1$



Magnetic Losses

The frequency response of diamagnetic materials is similar to the electronic polarization frequency behaviour

The frequency response of the paramagnetic materials is analogous to the behaviour of electric dipole orientation

It is required to describe the response of ferromagnetic materials when subjected to oscillating magnetic field

Since the frequency behaviour is related to the magnetic energy losses, it is important to study these losses before describing the frequency behaviour

Hysteresis Losses

When a ferromagnetic material is subjected to an oscillating magnetic field at low frequencies, two types of losses can be produced:

a The variation of the magnetic field results in circulating currents in the material called **eddy currents**

b. The movement of domains needs and disperses some energy, which represents intrinsic magnetic losses called **hystereses losses.** Due to the high value of μ_r for ferromagnetic materials, the behaviour is not linear for fields with high values

Hysteresis Losses

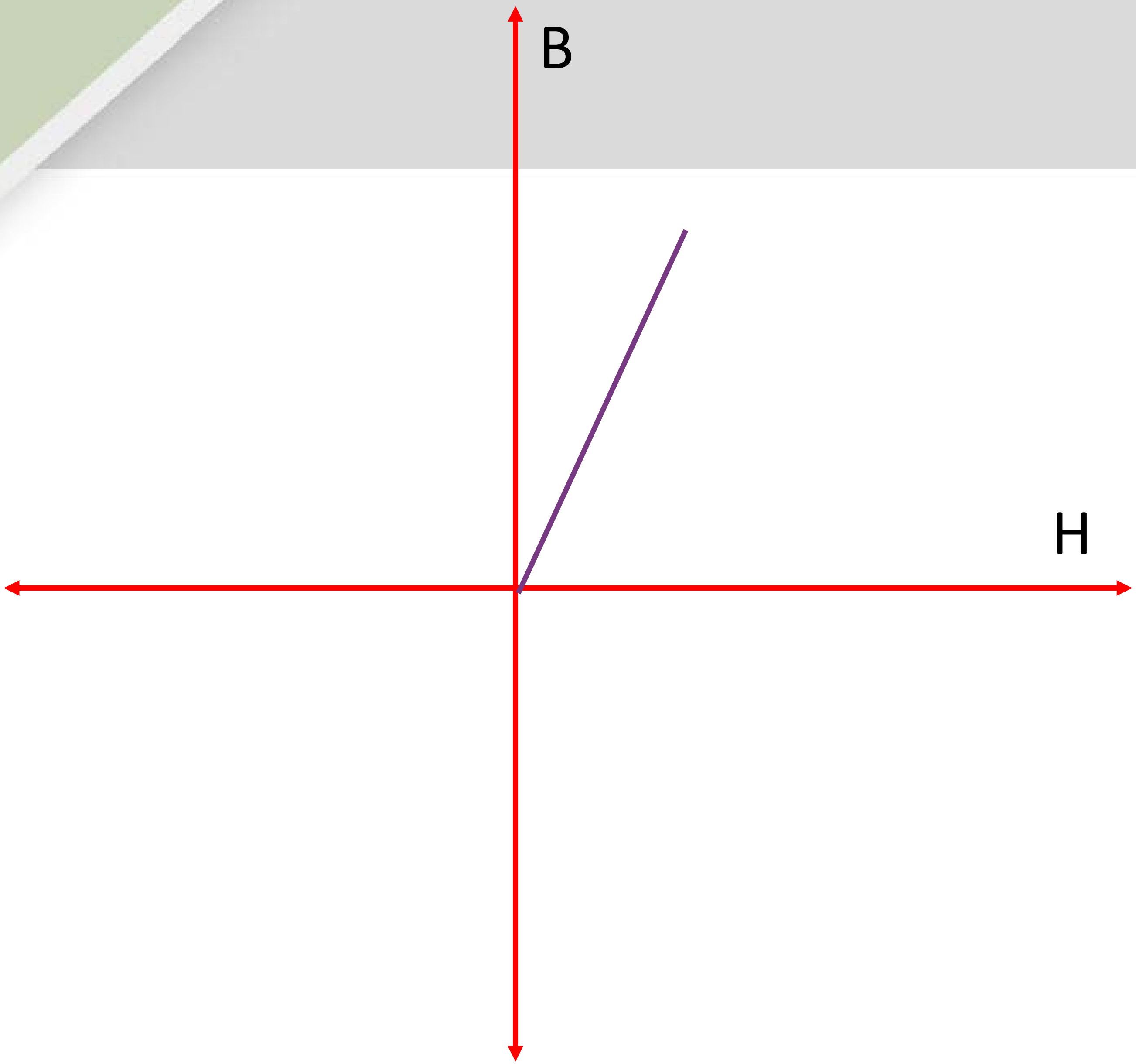
The increase in $\vec{M}$ and B as a result of increasing $\vec{H}$ to high values is not as the increase of $\vec{H}$

The magnetization density is not increased to the expected value but saturates

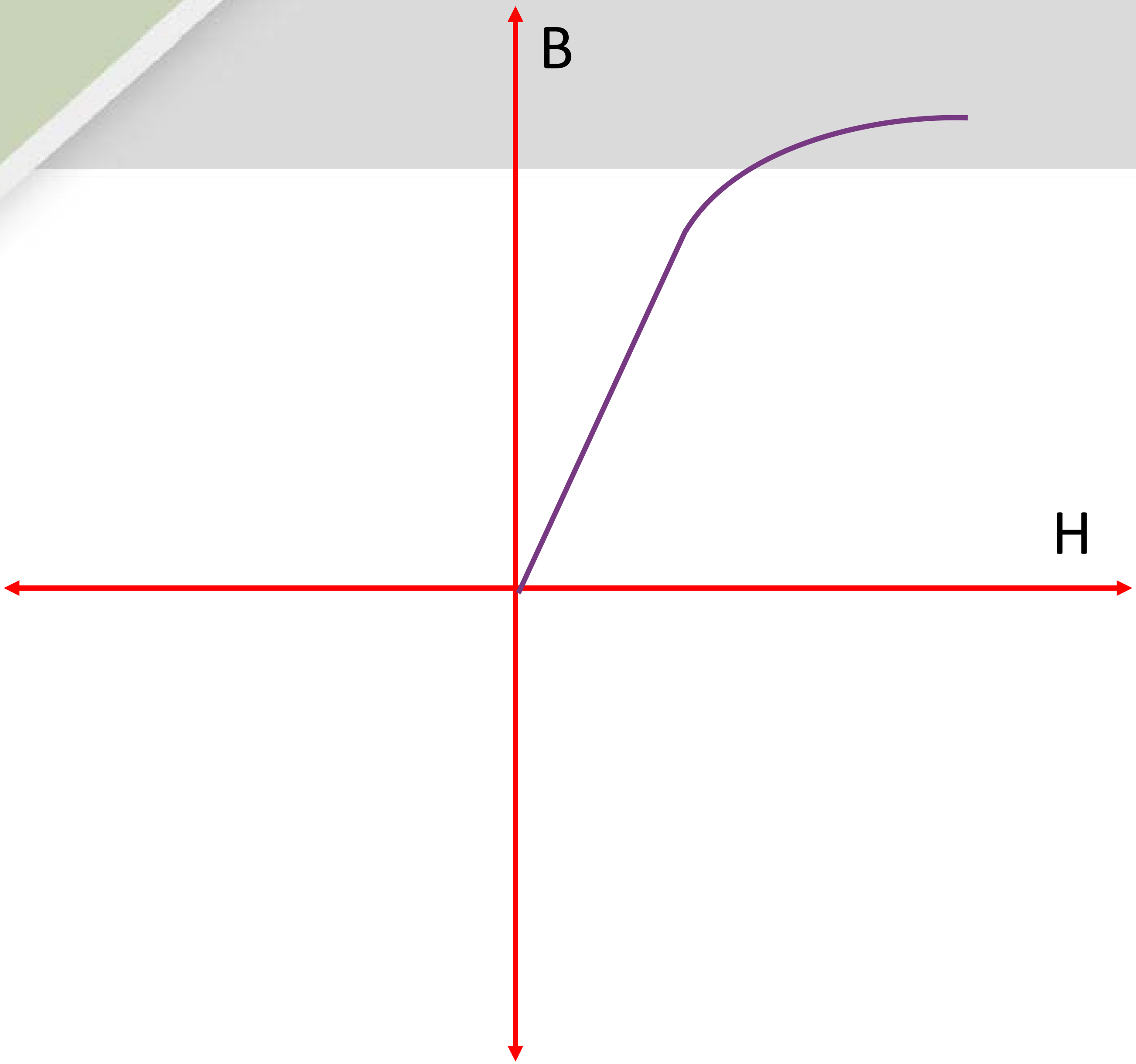
The maximum value of $\vec{M}$ is called the saturation magnetization density

The fast increase and decrease of $\vec{H}$ prevents the domains to align themselves quickly enough to keep up with the time-varying field

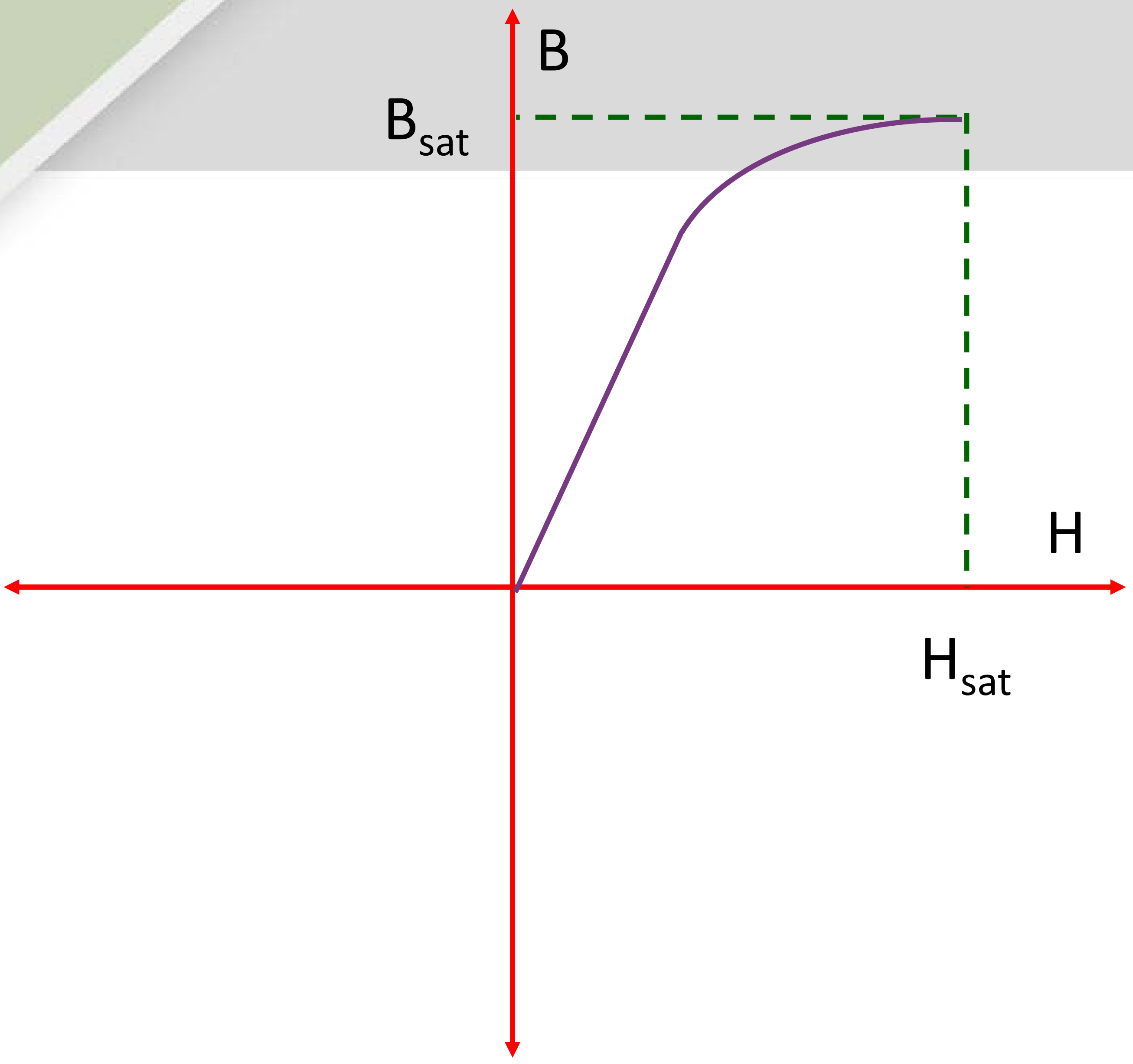
Hysteresis Losses



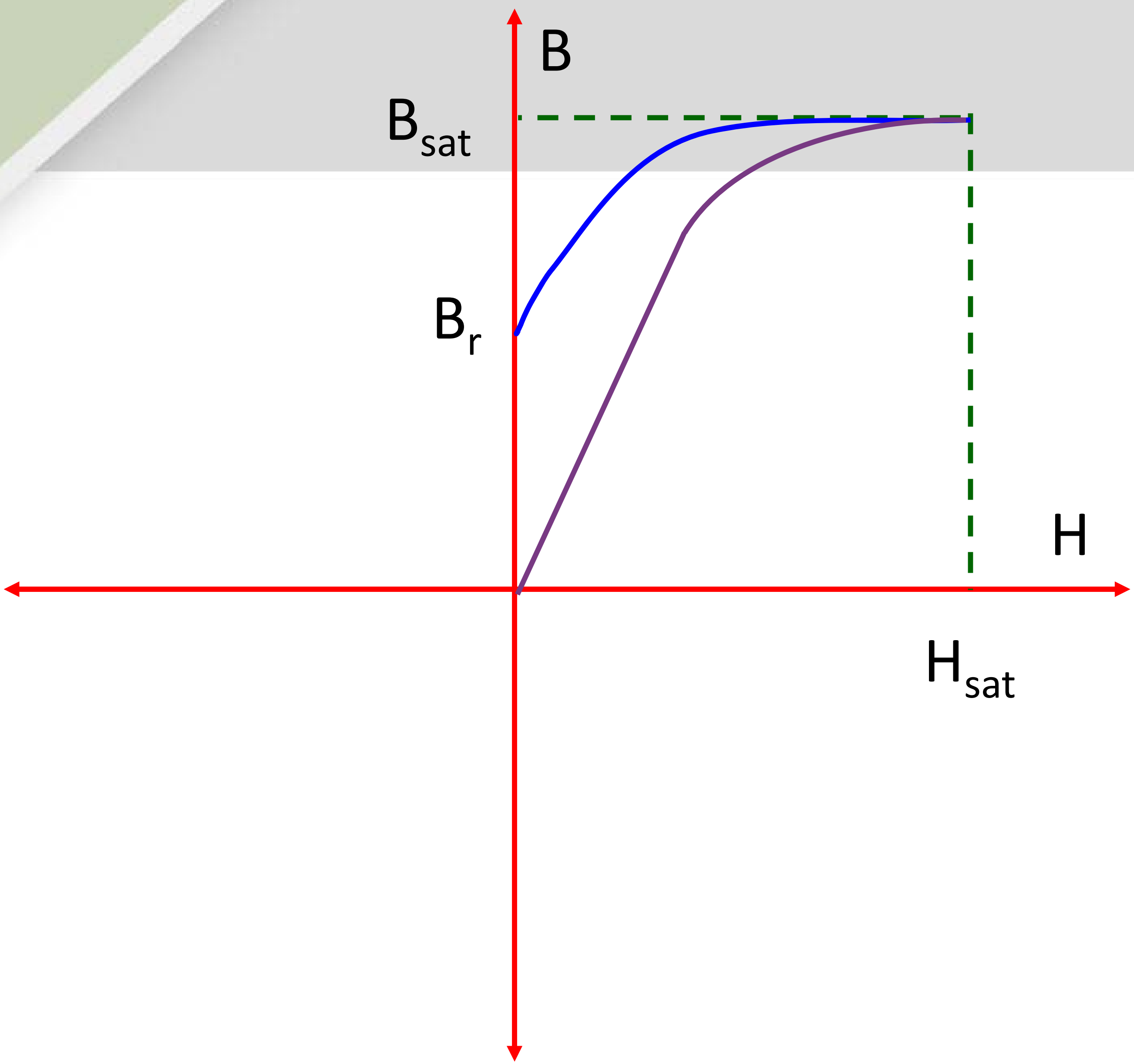
Hysteresis Losses



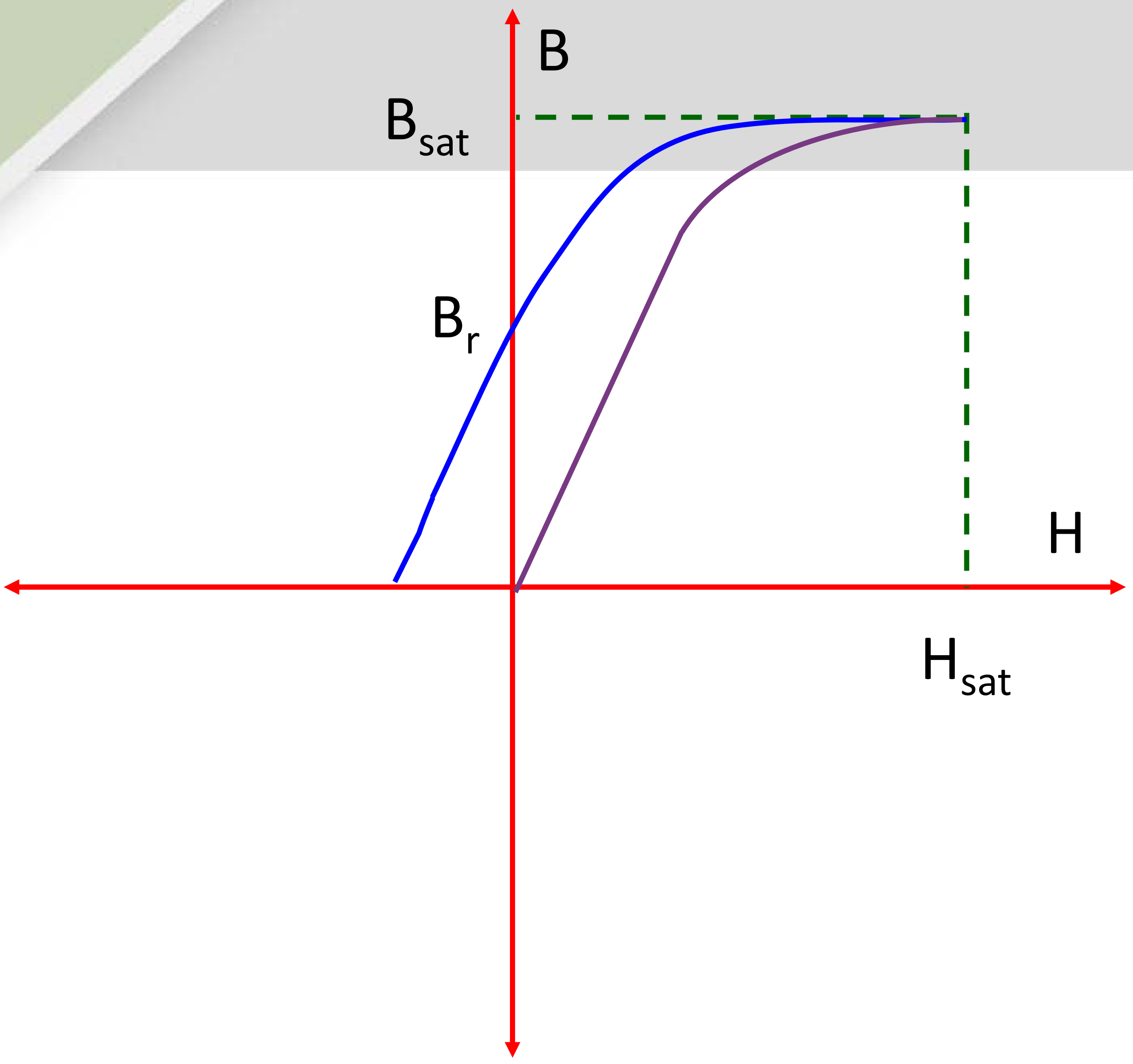
Hysteresis Losses



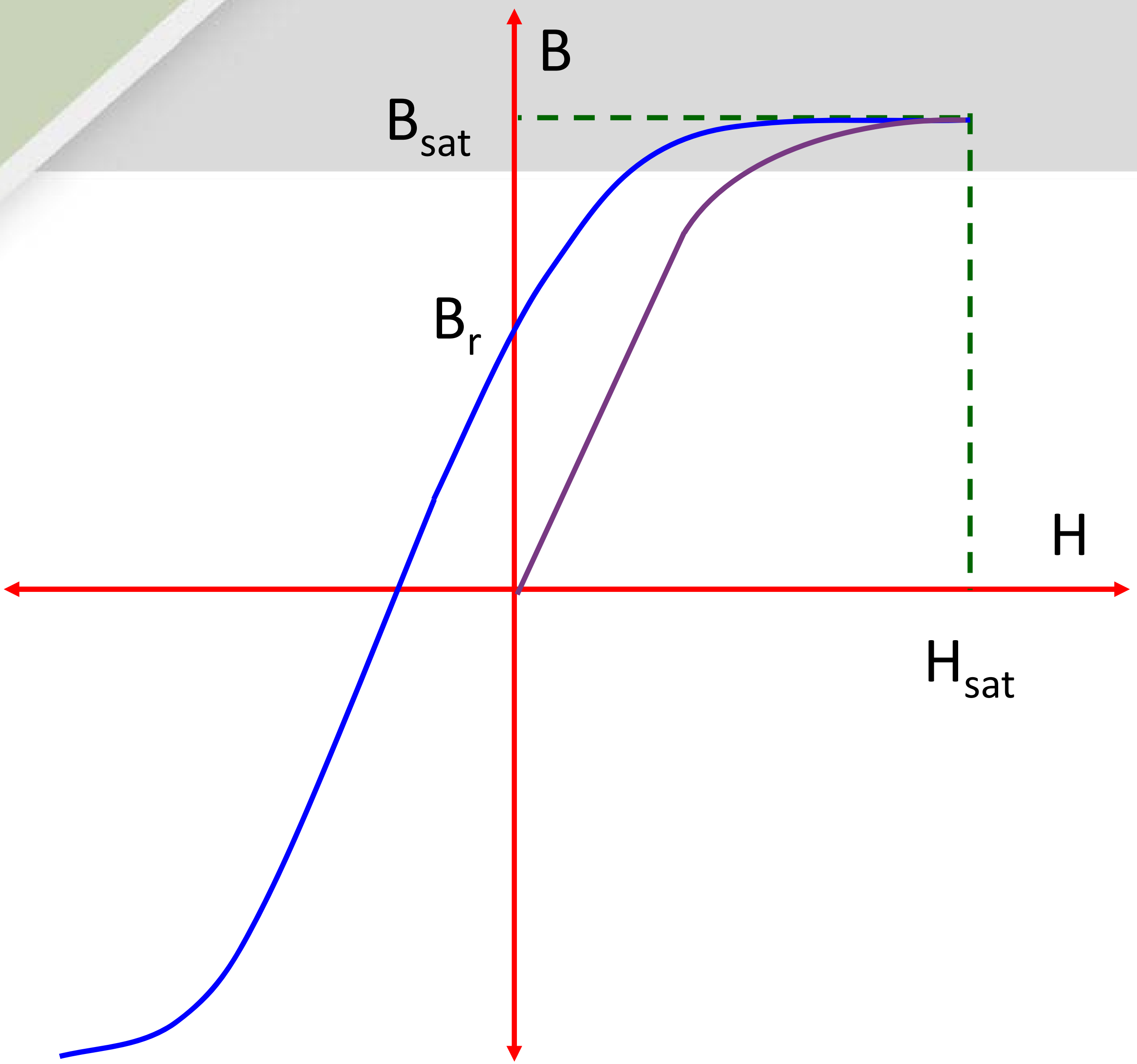
Hysteresis Losses



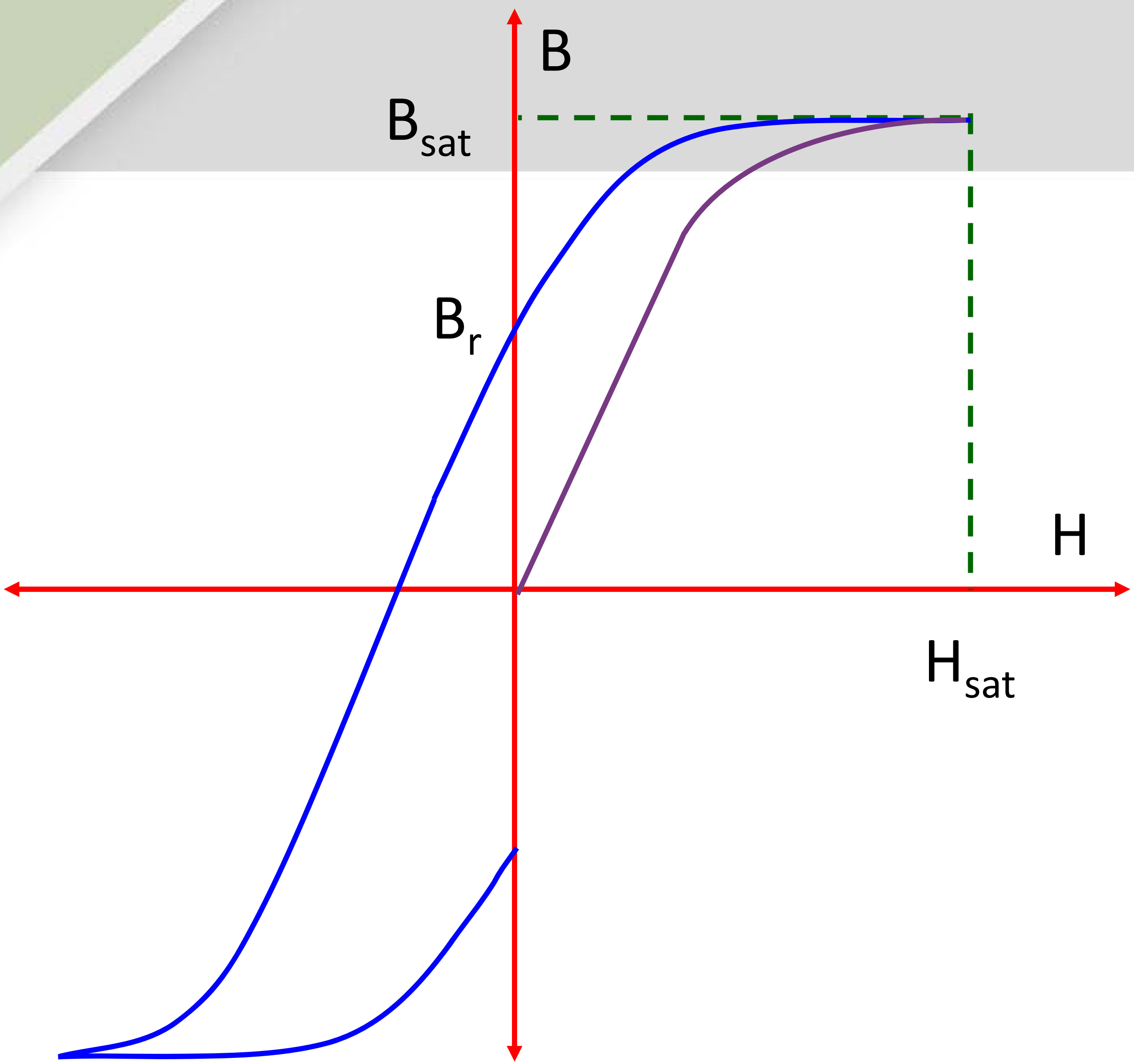
Hysteresis Losses



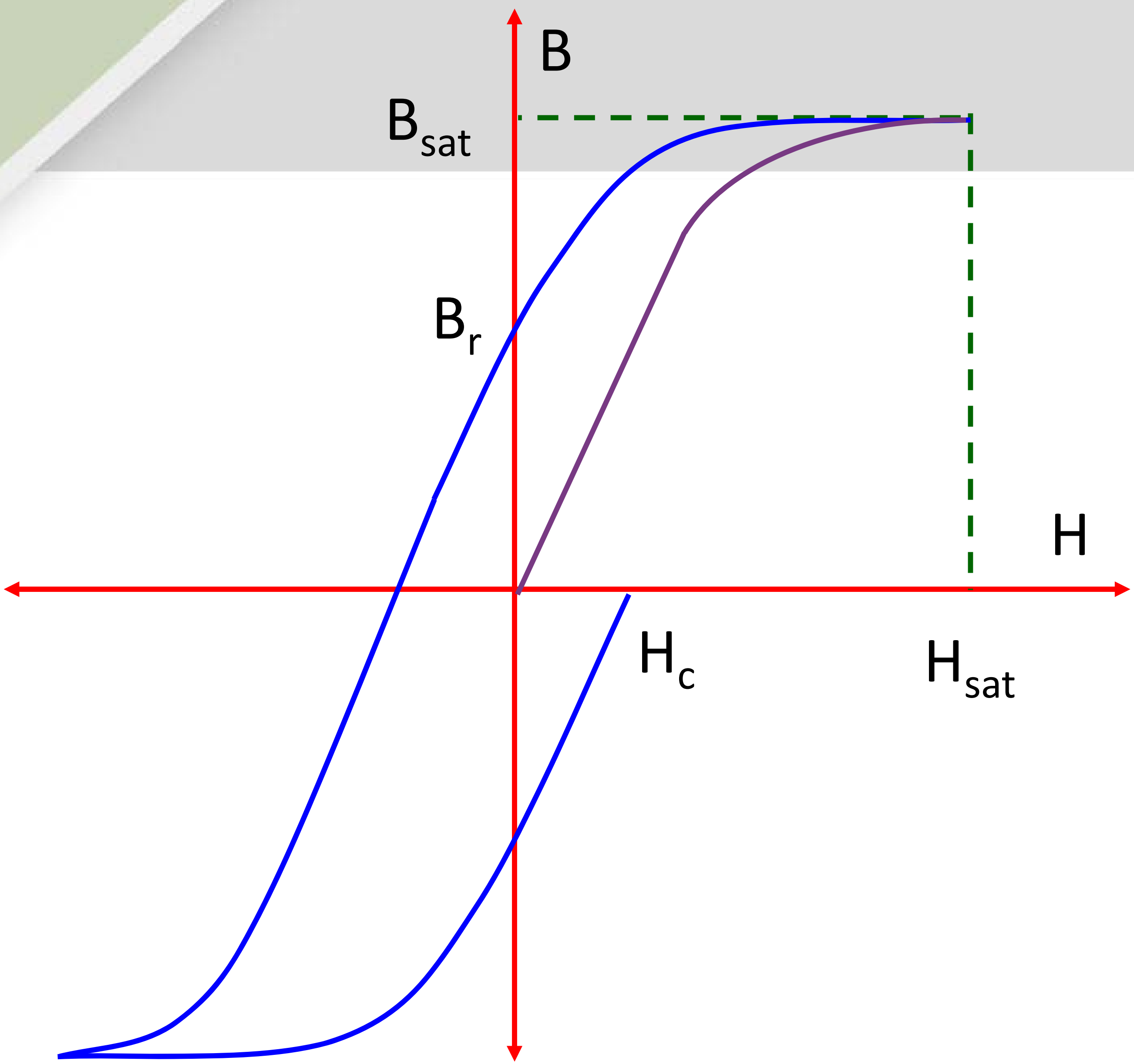
Hysteresis Losses



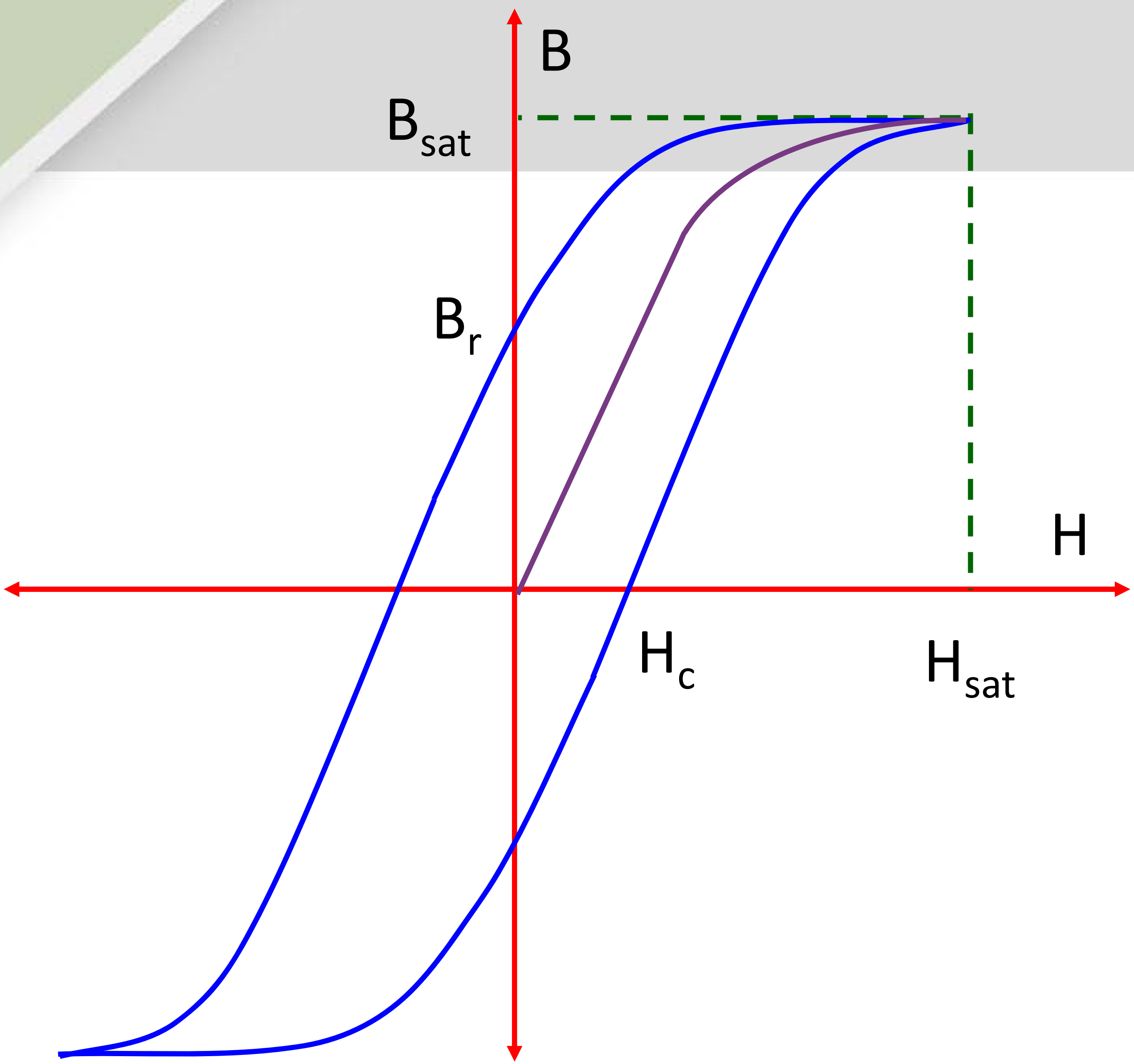
Hysteresis Losses



Hysteresis Losses

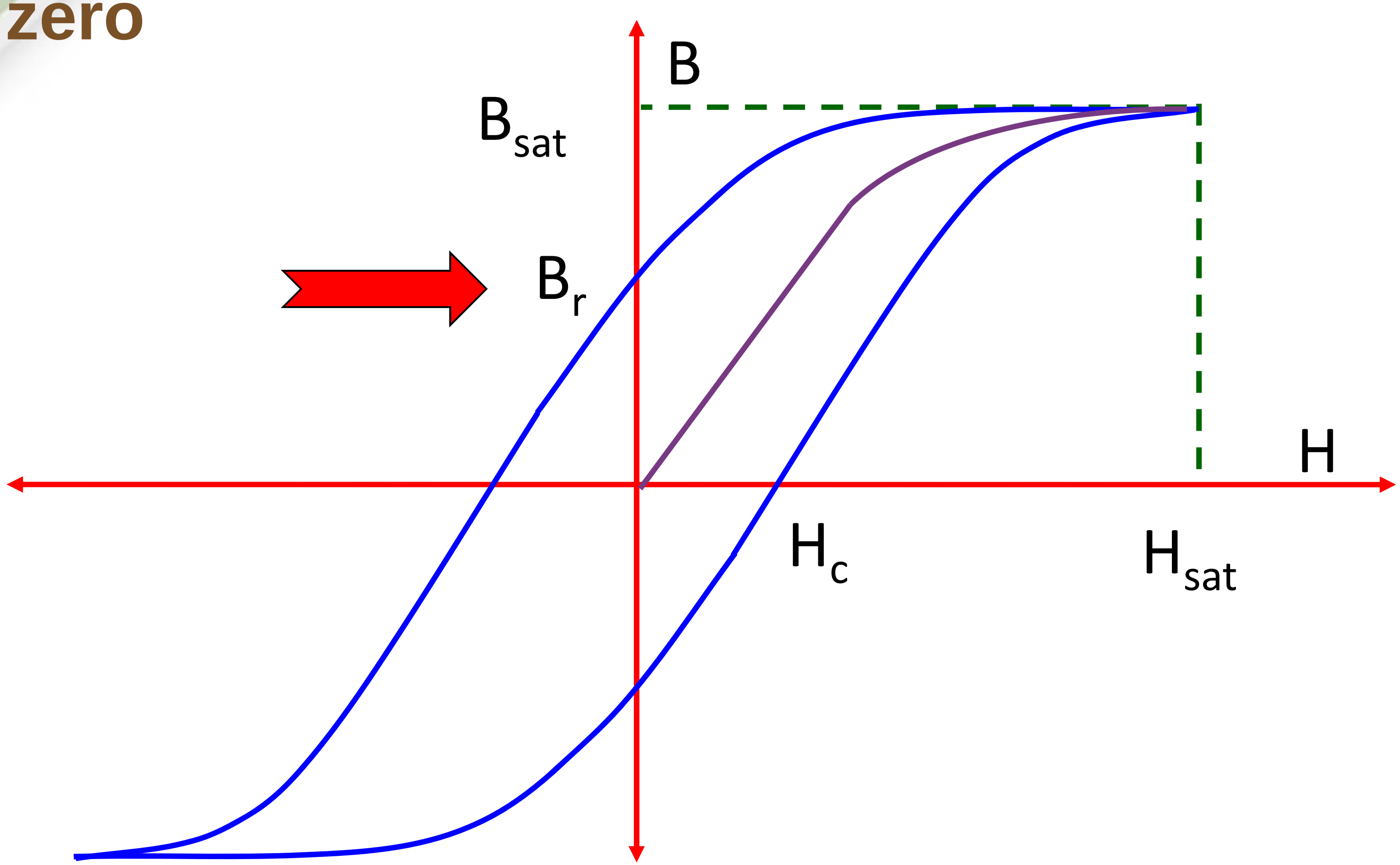


Hysteresis Losses



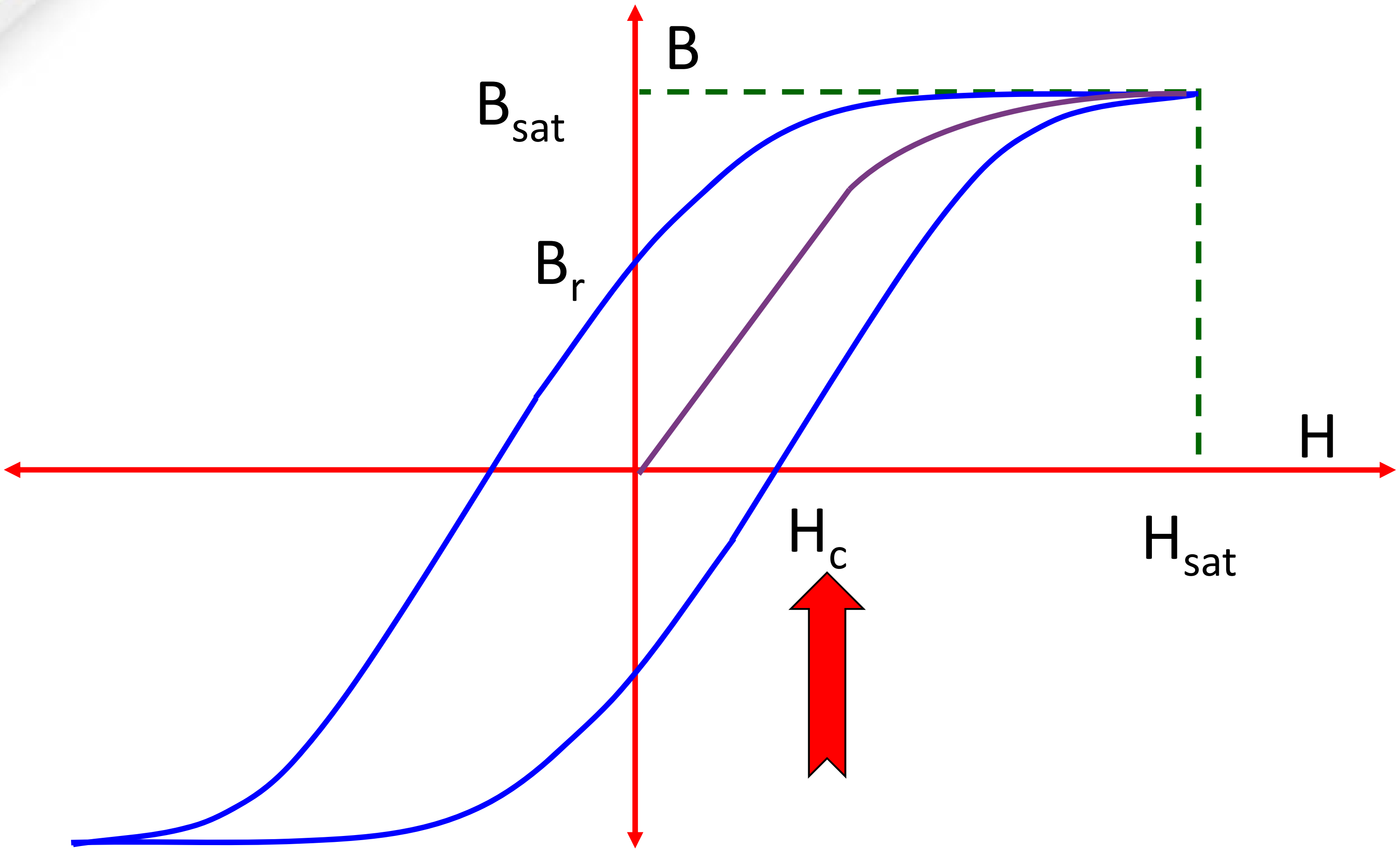
Hysteresis Losses

The magnetic flux density has a nonzero value called the <u>residual flux</u> density B_r when H is equal to zero



Hysteresis Losses

The magnetic field intensity has a nonzero value called **coercive force** H_c when B is equal to zero



Hysteresis Losses

An extreme case of ferromagnetism is found in permanent magnets, where M is constant regardless of the value of B and H

Only strong external fields or thermal disturbances can remove the magnetization of them

If the temperature of a ferromagnetic material is increased above a critical value (770 ^{o}C for iron), the material behaves like a conventional paramagnetic material

Both effects (i.e. eddy-current losses and hysteresis losses) are added together and the total energy lost is converted into heat

Hysteresis Losses

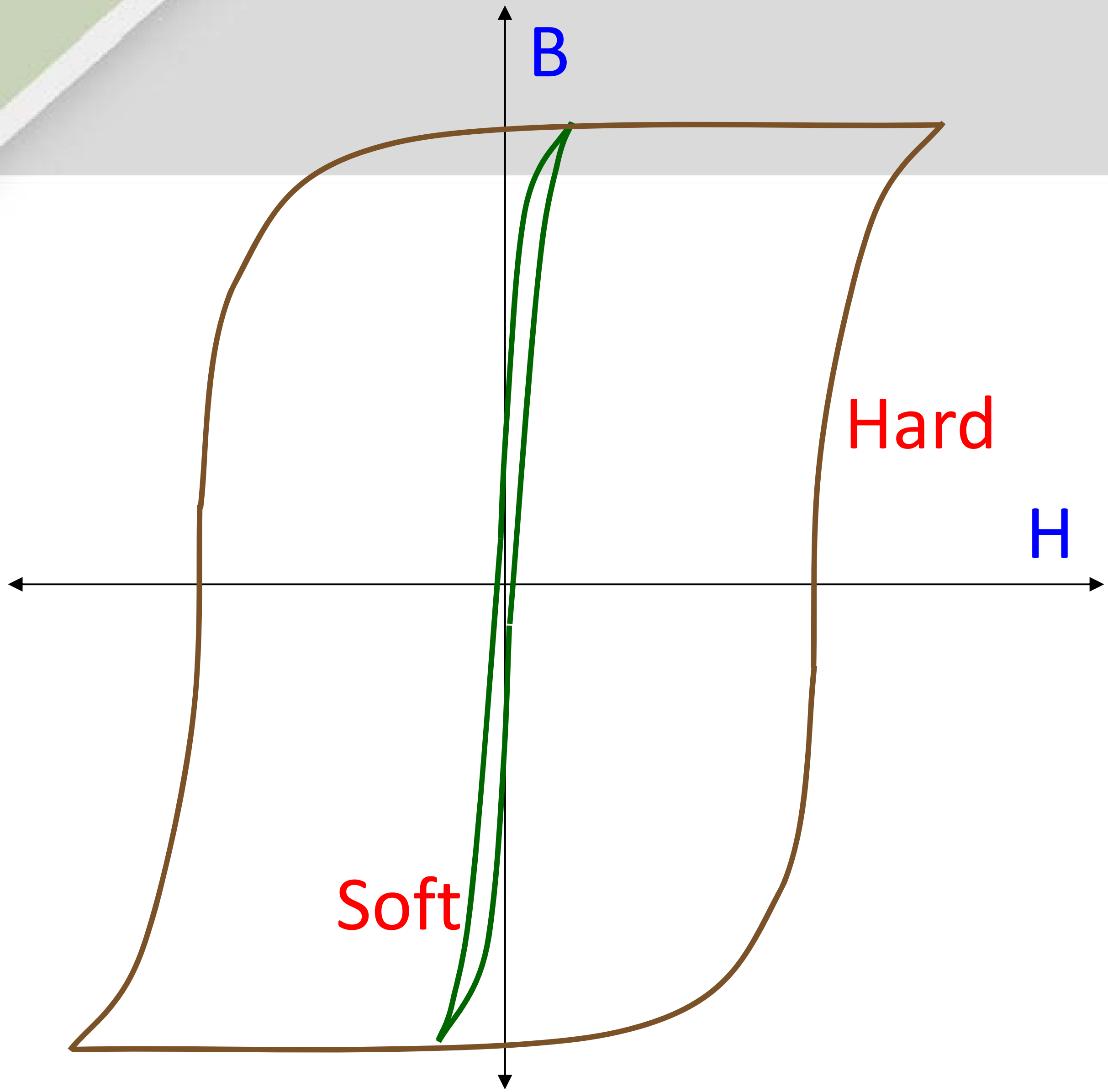
The magnetic losses depend on:

- The losses increase with the frequency (***f***) in both cases since the same losses are repeated each cycle
- The maximum magnetic flux B_{max} in both cases
- The conductivity $\sigma = 1/\rho$ for the eddy–current losses
- The magnetic field strength H for the magnetic losses

$$P_{loss} = P_{eddy} + P_{hyst} = \frac{\pi \cdot d^2}{6\rho} \cdot (f \cdot B_{max})^2 + 2f \cdot H_c \cdot B_{max}$$

P_{loss} is the total power loss per unit volume
d is the laminations thickness

Hard and Soft Magnets



Hard and Soft Magnets

The magnetic materials are classified according to their B-H curve into soft and hard magnetic materials

In soft materials, a large magnetic flux B can be produced by relatively low magnetic field intensity

The B-H loop in this case is narrow and the hysteresis loop has a small area

After removing the field, a small magnetization is left

For a reverse field, the magnetic flux is also reversed which means that the flux B generally follows H

They have small hysteresis losses

With a sinusoidal field intensity, the output will be distorted since the relation between B and H is not linear

Hard and Soft Magnets

Generally, soft materials are suitable for applications where repeated cycles of magnetization and demagnetization are involved

Examples are: transformers, motors and generators

On the other hand, these materials will not be suitable for applications that require a good permanent magnet

The remaining magnetization (remanence) after switching off the magnetic field H is small

Hard and Soft Magnets

Hard magnetic materials require relatively large magnetic field intensities

The magnetization can be switched between + B and -B with suitably high values of field intensity

They have a broad shape

If the field direction is reversed, the polarization remains without significant change unless the value of the field intensity is high enough to switch the magnetization direction completely

Very high Ferromagnetic losses

They are used as permanent magnets for magnetic storage of digital, data, where the status ^{+}B and ^{-}B represent 1 and 0 respectively

Hard and Soft Magnets